Real-time Simulation of an Integrated Electrical System of a UAV

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Abstract

Vives College University and Kulab (KU Leuven University campus Ostend) in Belgium are undertaking an aeronautical research program about the development of a new Unmanned Aerial Vehicle (UAV). Since the UAV is completely electrically powered, the analysis of the energy management of the integrated electrical system was critical to the development of the UAV. LMS, A Siemens Business, i s involved in the project to support the development of a multi-physics simulation model for electro-thermal analysis of the aircraft. This paper reports on the subsequent investigation of integrating the detailed electrical system model for a Pilot-in-the-Loop simulation. In order to perform this simulation, the model of the electrical system was converted into a real-time simulation model. The aim was to perform more realistic flight simulations to evaluate the performance of the aircraft before its first flight by taking into account the electrical system's behavior. Furthermore, the behavior of the electrical system can be directly assessed during and after the Pilot-in-the-Loop tests. Additional research outcomes include the suitable level of detail of the electrical system that should be taken into account for Pilot-in-the-Loop simulations. The research outcome was evaluated with a number of simulations that assessed the effect of the electrical system model. It was concluded that the proposed simulation architecture is suitable to take into account the effect of the electrical system on the aircraft flight dynamics.

Introduction

An Unmanned Aerial Vehicle (UAV) is an aircraft without a human pilot on board. Its flight is controlled either autonomously by computers in the vehicle, or under the remote control of a pilot on the ground or in another vehicle. The current Unmanned Aerial Vehicles (UAVs) technology offers feasible technical solutions for airframes, flight control, communications, and base stations. In addition, the evolution of technology is miniaturizing most sensors used in airborne applications. Hence, sensors like weather radars, multi - spectrum line-scan devices, etc. in addition to visual and thermal cameras are being used as payload on board UAVs. As a result UAVs are becoming efficient platforms that can be applied in scientific/commercial remote sensing applications [7].

UAVs may offer interesting benefits in terms of cost, flexibility, endurance, etc. Even remote sensing in dangerous situations due to extreme climatic conditions (wind, cold, heat) are now seen as possible because the human factor on board the airborne platform is no longer present.

Vives College University and Kulab (KU Leuven University campus Ostend) in Belgium are undertaking an aeronautical research program about the development of a new Unmanned Aerial Vehicle (UAV). The UAV is aimed at performing scientific missions along the Belgian coast line above the North Sea. The main performance requirement of the UAV, named Litus, is to be electrically powered with a range of 160km and a payload up to 5kg. The construction was performed in 2013. Test flights of the Litus are planned in the summer of 2014.

Since the UAV is completely electrically powered, the analysis of the energy management of the integrated electrical system is critical to the development of the UAV. LMS, A Siemens Business, is involved in the project to support the development of a model for electro-thermal analysis of the aircraft [4]. Therefore it has used its multi-physics simulation software LMS Imagine.Lab that can used to model different systems like electrical, hydraulic, pneumatic systems. This paper reports on the investigation of integrating the detailed electrical system model for a Pilot-in-the-Loop (PIL) simulation. The objective is to perform very realistic flight simulations that take into account the electrical system's behavior in order to evaluate the performance of the aircraft before it first flight. At the same time, the enhanced PIL simulation can be used to identify the internal states of the modeled aircraft systems during and after the simulation. These are, for example, the state-of-charge of the batteries, currents and thermal effects in the electrical systems.

The layout of this paper is as following. In section 2, the electrical network of the UAV will be described. In the subsequent section, the conversion to a real-time simulation model is discussed. In the next section, the Pilot-in-the-Loop setup is described. The evaluation of the PIL simulation is described in section 5. In the final section, conclusions are drawn and possible future work is identified.

Description of the UAV

Design Overview

During the conceptual design stage, several different aircraft configurations were investigated. This ranged from a conventional configuration to a twin-boom configuration. Eventually, a canard configuration with swept wings and a vertical tail at each wing tip was chosen for its aerodynamic efficiency (Figure 1) [1]. The final design resulted in a UAV which has an overall span of 5.87m and a length of 3.43m and which can cruise at 80km/h for 2 hours with a payload of 5kg, meeting the requirement of a 160km range. The maximum take-off weight will be 65kg. A propulsion system of two electrical brushless DC motors was selected in order to minimize the environmental impact during operations by avoiding gas emissions and reducing noise emissions. A push-configuration with 2 independent propulsion systems was selected to comply with safety requirements.

Figure 1. Vives Litus UAV [1]

Electrical Network

There are 5 physical separated electric circuits in the UAV:

1. Control. This circuit controls the aerodynamic control surfaces, sets the motor rpm and adjusts the nose landing steering angle. The circuit consists of 2 receivers, 1 RRS (Redundant Receiver System), 1 Powerbox which is powered by 2 batteries, all the servos, and a motor control output signal. The receivers receive the signal from the ground transmitter. The signals are compared by the RRS and the best signal is sent to the Powerbox. The Powerbox will block an output in case an error occurs such as short circuit or an over current. This provides additional redundancy. The Powerbox outputs control all servo's of the control surfaces and the nose gear. It also gives a motor setting to the speed controllers for the propulsion motors.
2. Propulsion left: This circuit supplies power to the left motor. The circuit consists of battery pack 1&2, speed controller 1 and the left motor with propeller. The speed controller gets its setting from the Powerbox. It regulates the required voltage accordingly to obtain the required rpm and thus the required thrust.
3. Propulsion right: This circuit supplies power for the right motor. This is a similar circuit as Propulsion left but with battery pack 3&4, speed controller 2 and the right motor.
4. Lights: This controls all the lights, which includes navigation, anti-collision, etc.
5. Payload: Any electrical circuits of the payload will be completely separate from the aircraft electrical circuits. Hence, it will also need separate batteries.

Figure 2 shows the architecture of the main electrical circuits (control, motor left and right) and Figure 3 shows the location of the different components in the aircraft.

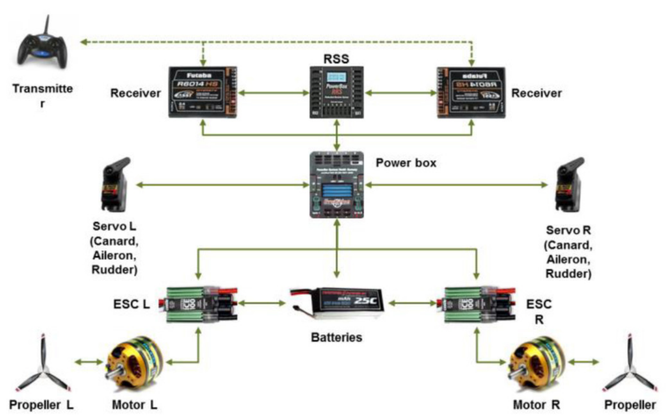

Figure 2. Vivis Litus electrical network architecture

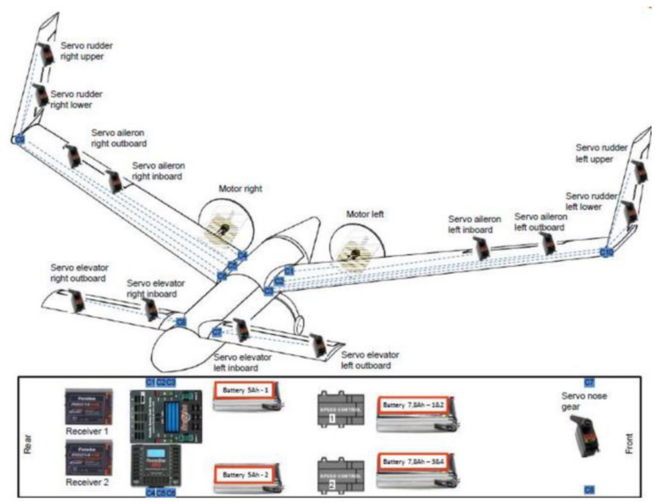

Figure 3. Location of main electrical components

Simulation Model of Electrical Network

Off-Line Model

During the design phase of the project, simulation models of the electrical network were created with the multi-physics simulation software LMS Imagine.Lab AMESim [6]. First, the electrical system that will be used during the test flights was completely modeled. This included models of the energetic behavior of all main electrical components:

- 2 receivers
- RRS
- Powerbox
- 13 servos
- 2 motors
- 2 ESCs
- 2 propellers
- 4 battery sets

Also the input control signals were modeled and are used to control the behavior of the electrical system. The objective of the electrical system model was to support the sizing of the components and batteries to achieve the required performance. Therefore, the modeling of the components focused on their energetic and thermal behavior and not on their dynamic behavior. The energetic behavior of all components was validated on test benches. This included a test bench of the motor with propeller for which also the propeller torque and thrust were measured, together with the power consumption of the motor and its electronic speed control (ESC). The top-level view of the simulation model is shown in Figure 15 in the appendix.

Afterwards, the electrical system model was also extended with thermal behavior of all components inside the fuselage to identify if additional ventilation of the fuselage is needed or dedicated cooling of some components. Outcome of these simulations was that cooling was needed for the ESC.

Real-Time Model

The real-time simulation of complex systems has become recently possible due to technological breakthroughs [3][5] and recent advances in computation power and multi-core processor architectures. In this case, recent improvement in the efficiency of the LMS Imagine.Lab AMESim solver has enabled the use of dynamic simulation models of relatively complex systems in real-time. As result, Software-in-the-Loop, Hardware-in-the-Loop and Pilot-in-the-Loop applications can now make directly use of physics-based simulation models that are created during the design phase of the system. This removes the need to create new approximation models. Moreover, the key physical parameters can still be changed for real-time applications.

However, not all simulation models can be run in real-time. First of all, the total duration of the simulation needs to be less than time that is simulated but more importantly, the duration of every time step of the simulation should be faster than the simulated time. This means that very fast transient effects are difficult to simulate in real-time and hence the model should be adopted accordingly. This is in particular an issue when dealing with models of electrical networks. Finally, the component elements that are used in the simulation model should have no internal-states as this creates additional overhead and slows down the computation. This can be avoided by selecting alternative simulation models of a component.

In the case of the electrical network model of the Litus, all component elements used already are in form of a quasi-static description, except for the batteries. This means that the models did not include fast transient effects as this was not required for the energy management and thermal management analyses for which it was used. On the contrary, the model of the servo motors was extended to capture better their performance limits.

In the original simulation model, a servo motor was modeled as shown in Figure 4. Basically, a servo was modeled as a variable resistance where a look-up table contained the measured relationship between the servo rotation angle and the power consumption. There was also a look-up table to define the relation between in the user input and the servo force which was not used.

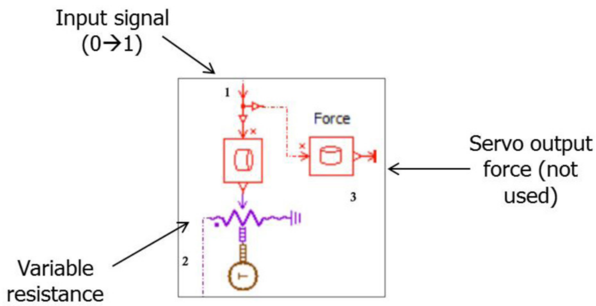

Figure 4. Original simulation model of servo motor

In the real-time model, the model of the servos was replaced with a model which also takes into account the maximum rotation speed of the servo. Additionally, the aerodynamic force is also taken into account based on an analytical formulation for hinge models of control surfaces. This is defined by the following equation from FAR-25:

$$M_{Cs} = C_D.\frac{1}{4}.\rho.V_l^2.S.c.(\sin \delta_d)^2 \tag{1}$$

Where:

- M_{Cs}: hinge moment
- C_D: aerodynamic drag coefficient
- ρ: air density
- V_l: airspeed
- S: control surface area
- c: chord length
- δ: angle of control surface

This formulation gives a force feedback to the servo but does not take into account the effect on the change in attitude of the aircraft. The aerodynamic force is compared to the servo force and the difference will result in a predefine rotation speed. The rotation speed is integrated to obtain the actual servo angle. This resulted in a model of the servo as shown in Figure 5.

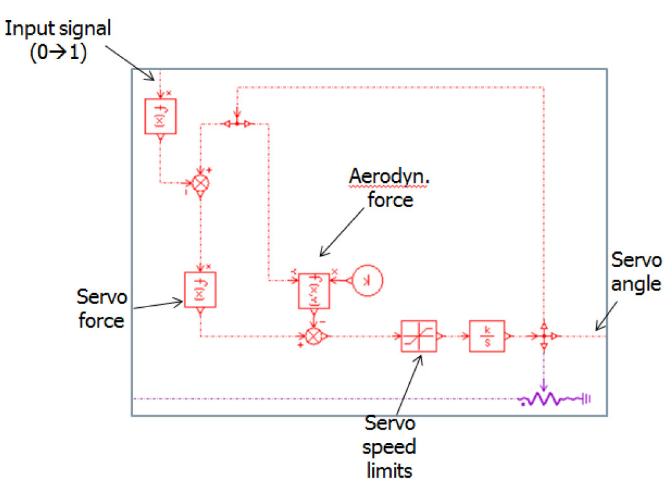

Figure 5. New model of the servo motor for RT simulation

The behavior of the servo motor was validated with a step input in an isolated model. The results shown in figure 6 confirm that initially the maximum rotation speed is used and subsequently the servo angle converges to an angle near the required angle.

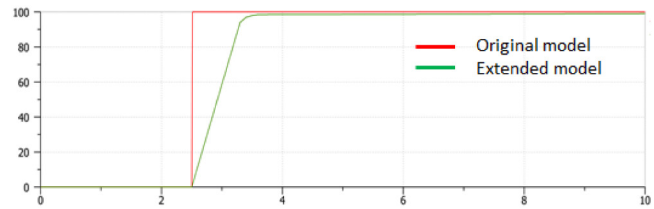

Figure 6. Step input response of new servo model vs. original servo model

Additionally, the models of some other electrical elements in the electrical network were adopted to eliminate implicit or depended states. This is a state or variable of a model that introduced an algebraic equation in the system of equations. Since the other components are defined by differential equations, a set of differential algebraic equations (DAEs) needed to be solved which required a different solver and more time than in case only different equations needs to be solved. Therefore, during real-time simulation only solvers for ordinary differential equations are supported and hence implicit states need to be removed from the model.

First, the two batteries for the control circuit were replaced by one model with a capacity that is equivalent to the original two batteries. This was needed because the two batteries model required an implicit state at the junction where they are connected together.

The original model also included a thermal model of the power cables for engines. Because this created additional internal states and was not required for the real time model, this model was removed. The changes to the battery model and thermal wire model are shown in Figure 7.

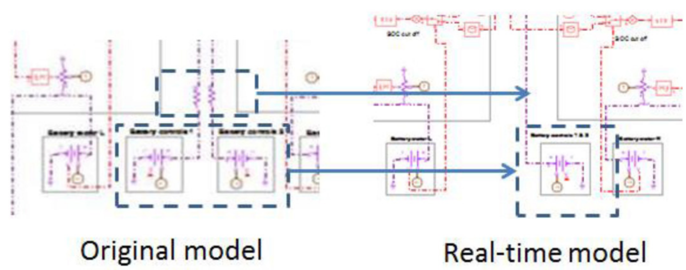

Figure 7. Modifications of battery and wire models

Additional simulations that compare the RT and off-line models confirmed that they result in the same behavior of the electrical network except for the servo properties.

Finally, in order for the real-time capable model to be able to interact with a human, hardware or other simulation models, an interface element needs to be added. This interface element, which is the same as a co-simulation block, makes the values of variables of interest available and retrieves values of variables that affect the simulation. In case of the Litus, the interface element receives the values for the transmitter, i.e user input for the throttle, ailerons, rudders and elevators, and it sends the instant angles of the ailerons, rudders and elevators and the thrust of the two propellers. The next section explains how this is used. The updated electrical network for RT simulation is shown in Figure 16 in the appendix.

Pilot-in-the-Loop Setup

Pilot-in-the-Loop (PIL) simulation is essentially a flight simulator. This means that a user interacts with a model that simulates the behavior of the aircraft. Typically, the user will have similar controls as the pilot on-board. These controls are linked to a computer that runs a behavioral model of the aircraft in real-time. The resulting attitude of the aircraft is subsequently sent to a visualization module which will show on a computer display the view from the aircraft cockpit and some flight parameters on virtual instruments. Due to the need to run the aircraft behavior model in real-time, this is usually a simplified flight dynamics model based on look-up tables that links pilot inputs directly to changes in the aerodynamic coefficients. As result, the behavior of the aircraft systems link the pilot inputs to the flight control surfaces is not taken into account and hence cannot be assessed during PIL simulations. Moreover, key states or parameters of these systems cannot be identified during the PIL simulations.

As stated in the introduction, this paper reports on the investigation to build a flight simulator of the Litus that takes into account the electrical system. Therefore, the real-time model of the electrical system that was discussed in the previous section will be used in a PIL simulation. The architecture of the simulator is as following.

The electrical system model in LMS AMESim is embedded as an S-function in a Matlab/Simulink model through the interface element. Subsequently, the Simulink model is connected to the open source FlightGear simulator software [2]. Simulink is used as intermediate to facilitate the set up and manages the time stepping between the different modules. However a direct communication between LMS AMESim and FlightGear would also be possible but would require more implementation effort. FlightGear is used to compute the aircraft attitude with its flight dynamics module and perform the visualization. Consequently, the required aerodynamic coefficients of the Litus need to be provided to FlightGear. The user input devices are also connected to FlightGear. As a result, the throttle settings together with the aileron, rudder and elevator input are sent from FlightGear to Simulink and subsequently passed on to the electrical system model in LMS AMESim. The latter sends then the total thrust of two engines and the rotation angles of 1 servo of each control surface back to FlightGear via Simulink.

Finally, the flight dynamics module in FlightGear computes the attitude of aircraft that is visualized on the display. Because the simulator architecture is composed of several modules, it is possible to run them on separate CPU cores enabling parallel computation. This architecture is depicted in Figure 8. Figure 9 shows a photograph of the setup. In this case, the complete simulator was run on the standard workstation with a windows 64-bit operating system. Of course, higher performance can be achieved on a dedicated real-time platform. A time step of 1ms was used.

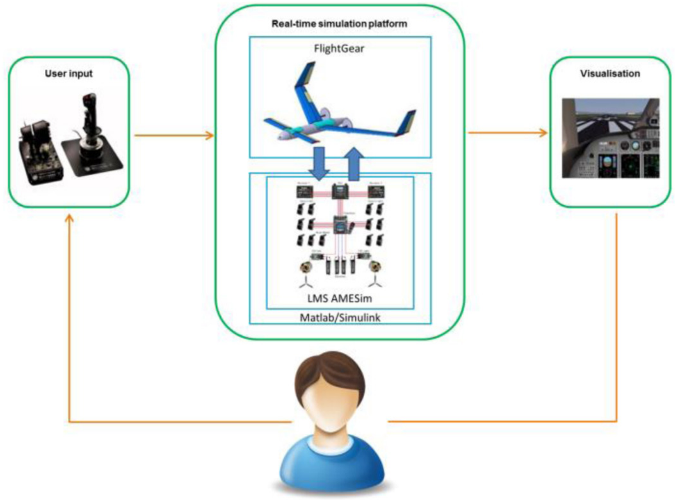

Figure 8. Pilot-in-the-Loop setup architecture

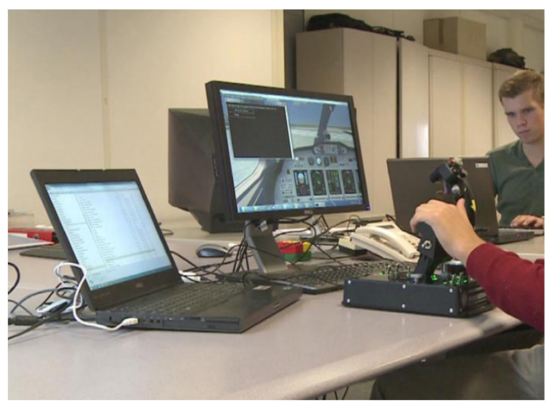

Figure 9. Pilot-in-the-Loop simulator setup

Evaluation

A mission profile, as shown in Figure 10, was flown with the flight simulation that was described before. It is composed of 5 phases. First is the take-off phase duration which the throttle is set to maximum (100%). This phase takes about 10s. Subsequently, there is the climb phase where the throttle is set to 90% and the elevators setting are increased. The climb phase is performed for about 100s.The next phase is the cruise phase where the thrust is set to 75% and the elevator settings are reduced. This is maintained for about 400s. Finally, there are the descent and landing phases where the thrust of the engines is further reduced.

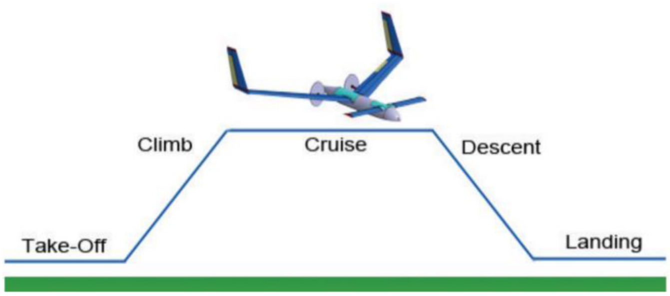

Figure 10. Mission profile flown with flight simulator

The thrust recorded from motor 1 during the take-off, climb and cruise phases is shown in Figure 11. The corresponding state-of-discharge of the battery pack is shown in Figure 12.

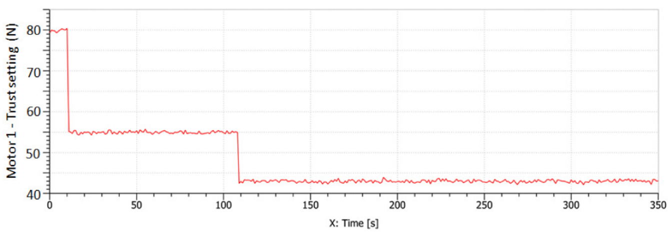

Figure 11. Recorded Thrust motor 1 (Take-off → cruise)

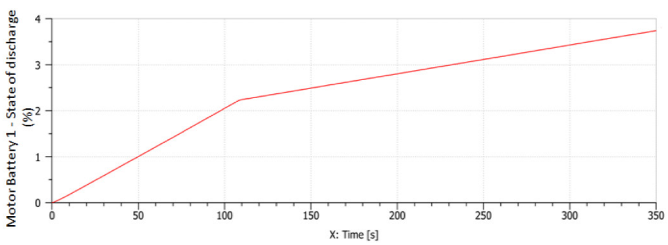

Figure 12. Recorded Battery 3&4 state-of-discharge

Furthermore, a roll maneuver was executed during cruise. Figure 13 shows the Pilot roll input and the corresponding rotation angle of the servo actuator. Figure 14 compares the resulting roll angle and roll angle of the same maneuver but were the user input is sent directly to the flight dynamic module, hence without servo properties. This latter plot illustrates the effect of the electrical system model on the flight dynamics of the aircraft.

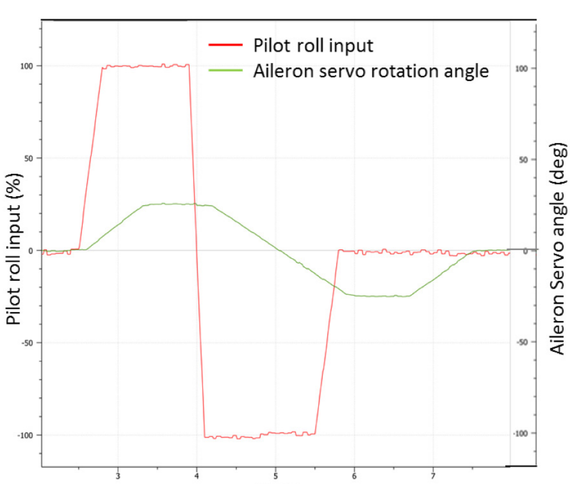

Figure 13. Comparison pilot roll input vs aileron servo angle

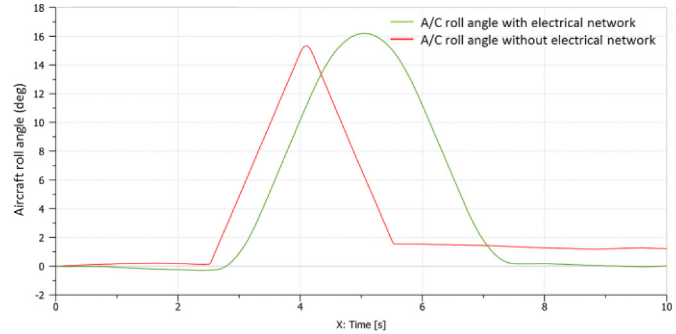

Figure 14. Comparison aircraft roll angle with and without electrical system model

Conclusions

The electrical network model of the Litus UAV that was created during the development phase has been successfully used as a real-time capable simulation model without major changes. This simulation model has been coupled with flight dynamics and visualization modules of the open source simulation software FlightGear. It was demonstrated that during the PIL simulation key parameters of the electrical network can be visualized. Moreover the effect of the performance of the key electrical components, such as servo motors, on the flight dynamics can be taken into account during real-time simulation. Consequently, this research confirms that the proposed simulation architecture is suitable to take into account the effect of the electrical system on the aircraft flight dynamics. In the future, an investigation is anticipated to couple the same model of the electrical network and flight dynamics module to an autopilot hardware platform in order to tune and validate the autopilot performance. This would demonstrate a Hardware-in-Loop (HIL) application.

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Definitions/Abbreviations

UAV - Unmanned Aerial Vehicle

RT - Real-time

PIL - Pilot-in-the-Loop

APPENDIX

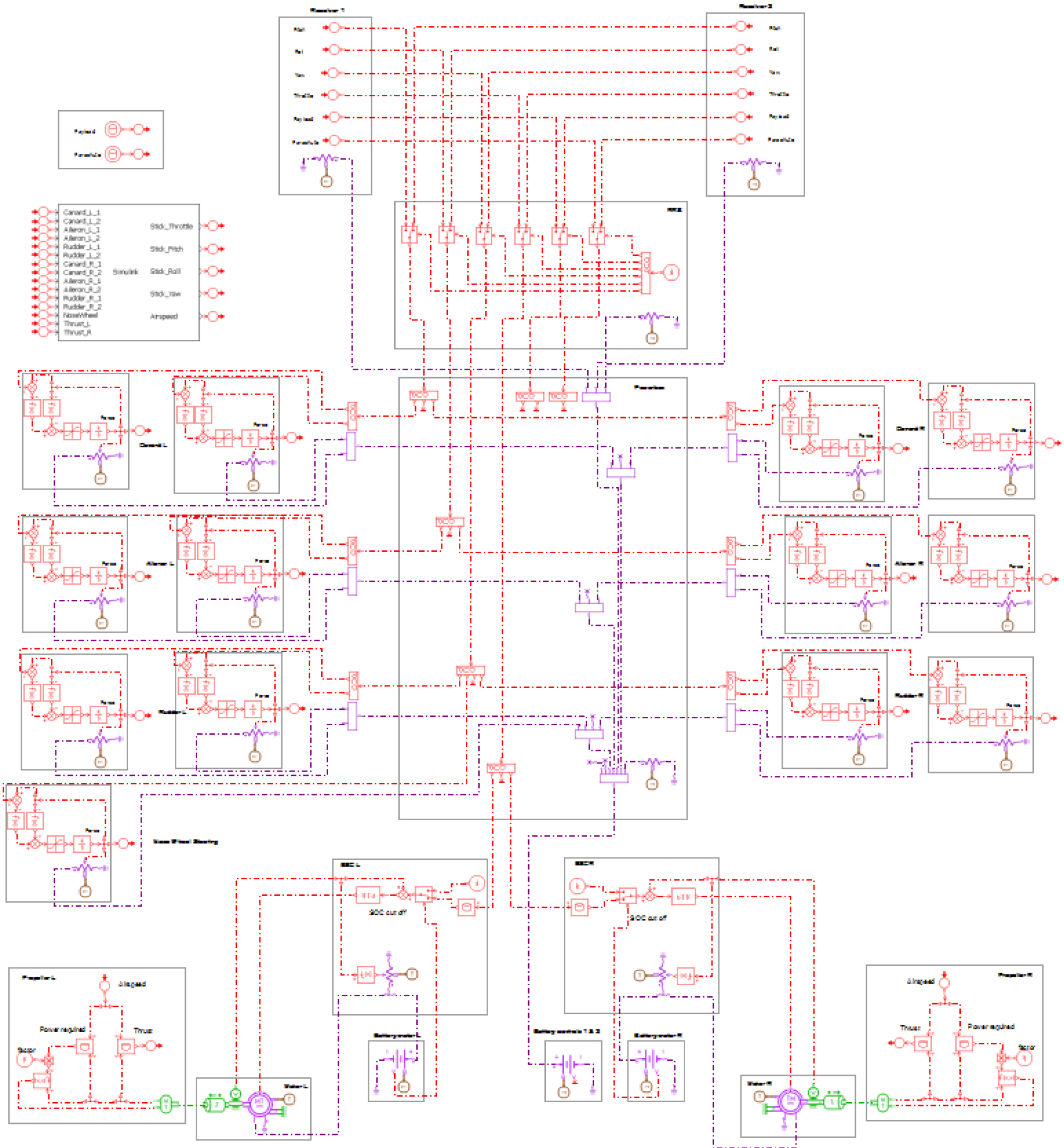

Figure 15. Simulation model of electrical network in LMS Imagine.Lab AMESim

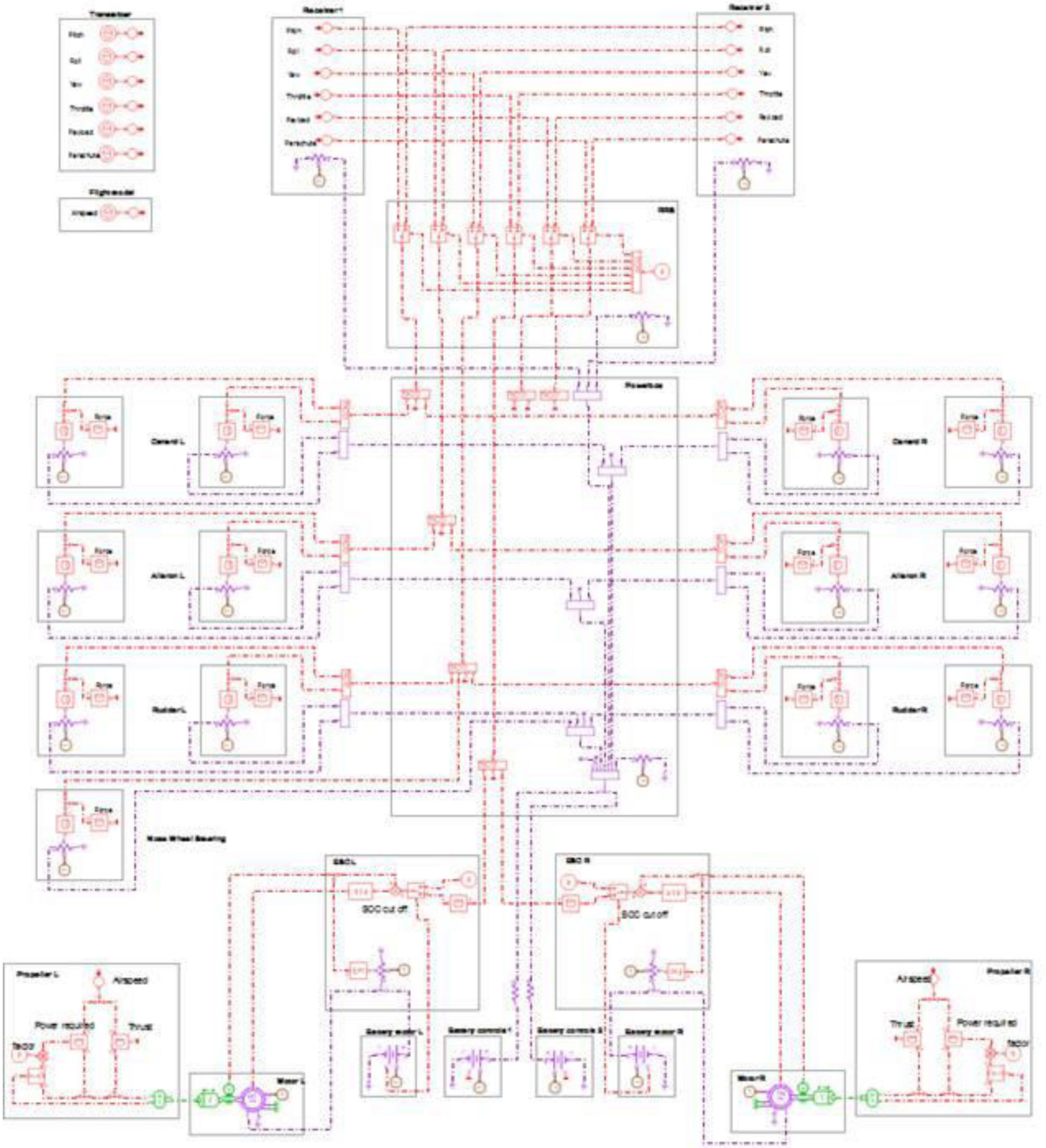

Figure 16. Litus real-time electrical network

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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